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Solar effects on terrestrial radio communication disturbances and associated tropospheric and ionospheric variations

S K Kar[1], A B Bhattacharya[2*] and Yuei-An Liou[1]

[1]Center for Space and Remote Sensing Research, National Central University, Chung-Li, Taiwan.

[2]Department of Physics, University of Kalyani, Kalyani-741 235, Nadia, West Bengal, India

E-mail : abb@klyuniv.ernet.in

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Abstract : The present state of knowledge on solar effects on terrestrial radio communication disturbances and associated atmospheric variations has been reviewed. An outline is given on the electrical behaviour of clouds with an emphasis on the thunderstorm activity, electrical discharges above and inside a cloud, global atmospheric variation and atmospheric electricity in relation to solar UV-variability. Effects of geomagnetic storms in the lower ionosphere and troposphere have been considered at length. Finally, the scope for future investigation is indicated.

Keywords : Thunderstorm, atmospherics, atmospheric electrification

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Plan of the Article

*Corresponding Author

1. Introduction

The entire gamut of terrestrial energy resources and associated systems owe their origin directly or indirectly to the Sun. However, the most vivid demonstrations of the terrestrial response to solar transient phenomena come from Aurora, magnetic storms, SWF (Short Wave Fade out) and PCA (Polar Cap Absorption), to name a few [1]. While the discovery of the ionosphere heralded the era of long distance communications, the geostationary satellite literally pushed it to the very zenith. To exploit fully the benefits of our radio environment, it is necessary to predict the solar variability and study the consequent changes of the ionospheric characteristics. Ionosphere affects radio communication in every band of frequency currently in use [2].

The electromagnetic radiation produces sudden increase of ionization in the various layers of the ionosphere [3–6]. The largest proportionate change in the ionization about ten times the normal value, occurs in the D region [7] which causes a sudden increase of absorption of radio wave producing short wave fade out (SWF). The propagation of long radio waves incident obliquely, facilitates causing sudden enhancement of natural Atmospherics (SEA) or sudden changes in ground transmissions producing sudden field anomalies (SEA), sudden enhancement of signals (SES) or sudden phase anomalies (SPA).

Many of the interferences in the ionosphere as well as on the geomagnetic field variations, may be derived from the secondary effects. Sun's influence on Earth's atmosphere manifests itself in three ways – (i) Radiation – UV, X-rays, visible and IR (ii) Corpuscular – energetic particles and plasma and (iii) Graviational tides. Variations in solar activity may be transients like solar flares, solar magnetic boundary passage, or solar proton events [8].

Several workers have taken into account short period and also long period variations in solar activity and correlated with atmospheric phenomena like atmospheric electricity, vorticity, ozone content and rainfall [9–11]. Satisfactory physical mechanisms connecting solar activity with weather, have not yet been evolved and the subject remains highly debatable. The vital problem is that the energy brought into the atmosphere by the processes associated with variable solar activity is much less than the energy of tropospheric circulation. Suggestions for physical mechanisms then can be drawn considering viable solar activity which may stimulate or trigger the tropospheric circulation.

2. The thunderstorm activity

Thunderstorms occurring world-wide, play a vital part within the global electrical circuit. It is believed that they act as power generators, building up a potential difference of about –250 kV between the Earth's surface and the ionosphere. Development of thunderstorms typically follows this pattern : the sunlit troposphere is heated by solar radiation reflected from the Earth's surface. Humid air piles up in unstable layers. Subsequently, instabilities develop and drive vehement convection which eventually can lead to the development of thunderstorm cells. Their average lifetime is between 30 minutes and two hours. Electrification and charge separation within a thunderstorm cell are based on microphysical phenomena which are not yet completely understood. The transfer of charges during collisions of ice crystals, graupel particles and rain drops seems to be essential for building-up of an electrostatic potential difference [12]. The charge separation is released in a bursty, more or less random fashion, through a sequence of lightning strokes. A lightning flash to ground consists of a complex pattern of single discharge processes and its optical appearance is dominated by the strong main discharge, the return stroke. Over 50 percent of all lightning discharges occur within the thundercloud and can be categorized as incloud-flashes. Their electromagnetic impulses can no propagate within the waveguide as effectively as the mainly vertically running cloud-to-Earth flashes [13].

The probability of occurrence and the activity level of a thunderstorm depends critically on the local time and closely follows the diurnal variation of the temperature [14]. The heating of the troposphere reaches its maximum over land during the local afternoon and its minimum in the early morning; over the oceans, the maximum is found after midnight and in the early morning. The diurnal variation of the temperature is much less distinct over the oceans than over the land. As the changes in air temperature and in the temperature-dependent water vapour storage capacity influence the buoyancy, the majority of thunderstorms develop over the continents. The important role of the ice phase in the thermodynamics of tropical atmosphere was considered by Williams and Renno [15]. Thunderstorms are very frequent at low latitudes over Africa, America and Southeast Asia within the Intertropical convergence zone, where the cumulonimbus clouds reach the greatest heights and produce the maximum number of lightning flashes [16]. Intracloud lightning is dominant in the central tropics but this may not be a powerful exciter of Schumann resonances.

In the meteorological synopsis, only the occurrence of a thunderstorm is reported, not its lightning activity. The only measure of the thunderstorm activity is a thunder day – a day on which within 24 hours a thunderstorm had been seen and heard. Obviously, the thunderstorm activity will be only poorly described by this kind of definition. A realistic simulation of the ELF (Extreme Large Frequency) excitation requires knowledge of the spatial and temporal distribution of the lightning rate. Brooks [17] was the first to summarize all available investigations of regional thunderstorm data to construct a global map of thunderstorm probability. From a report by Marriott [18] on the number of lightning flashes occurring in one thunderstorm and an estimate of the area which will be covered by an usual thunderstorm during its active phase, he concluded that about 1800 thunderstorms with 100 flashes per second are simultaneously active worldwide. The order of magnitude of this estimate is still accepted, although it is based on only one empirical investigation. Whipple and Scrase [19] derived the distribution of the global thunderstorm activity from registrations of the vertical electric field and from the results reported by Brooks. They specified the section of the Earth's surface covered by thunderstorms in the course of the day, depending on Universal Time. More correct descriptions were not simple to obtain : long-term investigations of global thunderstorm distribution agrees well with their work while short-time investigations have considerable deviations [20]. The most recent attempt to compare the diurnal curve of the atmospheric potential gradient and the global lightning activity was published by Williams [14]. In 1956, the World Meteorological Organization [21] (WMO) published maps of the average annual number of thunder days which summarized all the available observations. Modern methods of thunderstorm observations and lightning registrations are based on ELF- and very low frequency (VLF) reception at ground-based stations [22], investigations of electromagnetic waves in the range of the Schumann resonance bands [20,23], and satellite images [24]. Prentice [25] established a quantitative relation between the annual number of thunder days (depending on geographic region) and the lightning-rate per square kilometer and year. A commonly accepted value is an average number of about 100–200 lightning flashes per second worldwide.

3. Electrical discharges above and inside a cloud

C. T. R. Wilson postulated that electrical discharges could occur between thunderecloud tops and ionosphere [26]. Visual observations from earth of these above-cloud (AC) discharges are very rare. Recent National Aeronautics and Space Administration (NASA) space shuttle mission [27] and air-borne/ground-based experiments [28,29] have observed and documented AC electrical discharges. The different types of AC discharges are : 'jets' that appear to squirt from thundercloud top as bright blue flashes fanning upwards to altitudes of ~30 to 40 km [29] and 'sprites' that are diffuse, erect streamers, with bright tops extending to altitudes of ~60 to 90 km [29]. Several probable mechanisms for sprite formation have been theorized [30,31]; however, no suitable theoretical explanation for jets has been formulated.

To understand the occurrence of AC discharges, a laboratory experiment was designed [29] with crystalline particulate dielectric-air media to simulate these two types of electrical discharges above thunderclouds. It was not possible to replicate completely all complex atmospheric conditions in the laboratory that influence AC discharges; however, some very critical parameters have been investigated, *e.g.* break-down electric *E*-field, pressure, effective charge separation, and simulated thundercloud electrical conductive properties. This controlled experimental simulation was an attempt to recreate similar electrical discharges within or from a charged cell. Maurice *et al* [32] considered a basic experiment of electrical breakdown in the presence of particulate dielectric-air media with appropriate electrode separation. The discharges generated had some similar characteristics to that observed in the atmosphere and may provide insight into the complex phenomena of AC discharges. More details of this experiment are given in Jarzembski and Srivastava [33].

Sprites visibly extend to altitudes of 60 to 90 km, which implies intense electrical activity in both thundercloud top and upper atmosphere. As observed both in the atmosphere [28,29] and in the simulation, sprites appear to be associated with an intermittent intense bright discharge at the cloud top layer, causing the observed blue and white bright cloud top [29] which seems to be a precursor to sprites. Further, the result suggested a lowering of the upper atmosphere isopotential surface towards the electrically active cloud top which would occur in response to sudden changes in electric *E*-field due to a major discharge observed at the bright bluish-white cloud top [28,29] before the onset of the sprite. Thus, the motions of mesospheric/ionospheric electrons are considerable modified, produce transient, elongated, relatively more conducting, columnar regions in the mesosphere of high density electrons as they are accelerated towards the bright electrically active cloud top. The upper sprite bright red glow (occurring between 50 to 90 km) is probably due to this intensification of rapid free electron motion in a conducting column as well as similar sporadic long wire glow in the low pressure simulation. Mesospheric discharges and bright cloud top lightning occur together but may or may not be visually connected, as observed both in above mentioned simulation and in the atmosphere [29].

The upper sprite glow may be located in the mesospheric 'equalizing' layer at latitudes of 60–70 km where enhanced electric *E*-fields have been already found to exist [34]. This would assist in focusing electron motion from the upper mesosphere and lower ionosphere in response to electric *E*-field changes in the cloud top, causing intense heat and shock waves which may be the characteristics 'popping' sound heard during the occurrences of sprites [29].

4. Global atmospheric variation

Investigation of the effect of passage of solar magnetic sector boundary (SSB) on the zonal mean field shows that the temperature of the polar region in winter reaches a minimum on the 0th or first half day below 500 bm [35]. It is seen that at each level, the whole cooling in the polar region (90°–65°N) is same as the whole heating in the mid latitudes (60°–35°N). Response in the polar region must result from a change of northward heat transfer around 60°N, most of which is contributed by eddy heat flux. Geopotential heights at 30 mb level for the period 1972-78 for the northern hemisphere have been subjected to spherical harmonic analysis with a view to represent the global stratospheric circulation. Cross spectrum analyses of the first two spherical harmonic coefficients with the corresponding geomagnetic index *Ap* and the 10.7 cm solar flux, did not reveal any significant correlation between solar geomagnetic activity and stratospheric circulation on a global scale, in long-period variations. To investigate any preferential latitudinal response to solar signals, Fourier analysis has been made of the grided geopotential heights at 30 mb level along latitudes 20°N, 60°N and 80°N [36]. Cross spectral analysis of *Ap* and *F* 10.7 with the first two harmonics along each latitude circle indicates significant coherence in the semi annual variation in *Ap* and the first harmonic along 40°N and the second harmonic along latitudes north of 20°N; 10.7 cm solar flux did not reveal any significant correlation, suggesting that the solar particle radiation may be influencing the relation between the semi-annual waves in lower stratospheric circulation and solar geomagnetic activity [36].

5. Atmospheric electricity and solar UV-variability

Markson [37] first used the solar magnetic sector passage as an index of solar activity. He has discussed the role of atmospheric electricity in sun-weather relations. The solar controlled conductivity variations in the lower stratosphere over thunderstorms, control the current flow in the global circuit. This may ultimately influence cloud physical processes and thus the atmospheric energy. Reiter [38] has brought out convincing evidence for variation by 20% to 30% of the vertical electric field at the top of the Bevarian Alps (3 km high), with SSB passage during one complete solar cycle. The increase is larger at towards/away boundaries and in years of maximum sunspot activity. Air-earth current density decreases before the time of SSB crossing.

Markson and Miur [39] found that the earth's electric field intensity which is maintained by world-wide thunderstorm activity, varies in phase with galactic cosmic radiation. They inferred from the inverse correlations between the solar wind velocity and the ionospheric potential and galactic cosmic radiation, that the solar variability modulates Earth's electric field by controlling ionization. It would cause increase in the number of global thunderstorms and electrification of cumulous clouds.

The solar modulation of the Earth's electric field takes place through regulation of ionising radiation by magnetic discontinuities within the solar wind. The galactic cosmic radiation being the sole agent in ionizing the stratosphere and most of the troposphere, the Sun controls the atmospheric electrification mostly through modulation of galactic cosmic radiation [40].

Observational evidence suggests the presence of solar UV variability in the spectral range of 1750 to 3100 Å;

during the 11 year solar cycle. Callis and Nealy [41] determined using a 1-D photo-chemical model, the response of stratospheric temperature O_3 and N_2O constituent distributions to UV variability. They inferred an increase in globally averaged O_3, a decrease of N_2O at stratospheric levels and substantial temperature variations at higher levels due to increased UV flux in the range 1900 to 2100 Å.

6. Effects of geomagnetic storms in the lower ionosphere and troposphere

The variabilities of the solar wind and high-energy charged particle fluxes form an important channel of solar activity-influence on the Earth's atmosphere. There are many different components of this channel. Among these, often interrelated phenomena are the variability of the solar wind speed *Vsw*; the variability of the interplanetary magnetic field (IMF) *B* and of its components B_x (radial), B_y (azimuthal), B_z (north-south-southward turnings are very 'geoactive') : Earth crossings of the IMF sector boundary (heliospheric current sheet) : shock waves in the solar wind; high-speed streams in the solar wind; interaction regions in the solar wind; the modulation of galactic cosmic ray fluxes, including ground level events and Forbush decreases; solar cosmic ray bursts or solar particle events; relativistic electron precipitation events, including highly relativistic electrons; magnetospheric substorms; and geomagnetic storms. The effects of these phenomena on the atmosphere often overlap each other. The majority of the effects of solar wind variability manifest themselves through geomagnetic storms, magnetospheric substorms and changes of magnetic activity. Geomagnetic storms are believed to cause the largest global atmospheric effects among all the above phenomena.

The atmospheric region at heights from 0 to 100 km, may be divided into three (not independent) regions for easier treatment – the ionized lower ionosphere, the neutral middle atmosphere, and the lower atmosphere. The effects generated by solar wind variability and high-energy charged particles are well-developed and fairly well-understood in the lower ionosphere, whereas they are not so well-known or well-understood in the low-lying layers and in the neutral middle atmosphere, particularly in the stratosphere [42]. Effects of geomagnetic storms in the lower ionosphere and in the troposphere are still debatable.

The solar wind-related phenomena and high-energy particle bombardment of the atmosphere play a role primarily at higher latitudes. Some of these phenomena, *e.g.* geomagnetic storms or cosmic ray flux variability, also act at lower latitudes, even though their effects are much weaker there.

Simultaneous changes of *Vsw* and B_z, shock waves and high-speed streams in the solar wind are the main causes of geomagnetic storms. Also, the effects of crossings of the IMF sector boundary manifest themselves partially through changes of geomagnetic activity but predominantly, their effects on middle latitude atmosphere were summarized by Lastovical [43].

Galactic cosmic rays are responsible for the ionization of the lowest part of the lower ionosphere and of the lower atmosphere down to the troposphere. Galactic cosmic rays considerably affect atmospheric electricity. They also affect the chemical composition of the atmosphere, especially contributing to sources of odd nitrogen in the lower stratosphere [44]. Forbush decreases of the galactic cosmic ray flux, among other causes, deteriorate the ELF/VLF radio propagation in the Earth-ionosphere waveguide [45]. Lethbridge [46] reported some relations between the cosmic ray flux and thunderstorm activity. Other experimental evidence on the galactic cosmic ray flux – effects on tropospheric process was provided *e.g.*, by Tinsley *et al* [47]. A possible scenario of the cosmic ray effect on tropospheric process was proposed by Tinsley and Dean [48] and was developed further by Tinsley and Heelis [49]. The scenario is as follows : changes of the galactic cosmic ray flux cause changes in the tropospheric ion production, changes in the vertical air-Earth electrical current, changes in the rate of polarization charging of clouds *via* the accumulation of positive electrostatic charges on droplets near cloud tops, changes in the rates of ice nucleation (electro-freezing), changes in the rates of precipitation, net latent heat release, vertical motions and atmospheric vorticity, and changes in the general circulation of the troposphere. The above scenario cloud play a certain role in explaining the effects of geomagnetic storms on tropospheric processes because large geomagnetic storms are accompanied by changes in the galactic cosmic ray flux. However, several parts of this possible scenario are hypothetical and need to be confirmed by further investigations.

Solar proton flares eject streams of high-energy particles called solar cosmic rays. They are not directly related to geomagnetic activity, but strong SPE's (Solar proton event) are generally followed by geomagnetic storms. SPE's cause polar cap absorption (PCA) events in the lower ionosphere. SPE's conisderably increase the electrical conductivity in the high latitudes stratosphere [40].

SPE's play an important role in the neutral middle atmosphere, but not in the lower atmosphere. They produce odd nitrogen and odd hydrogen, with a subsequent ozone depletion [42,50], HO_x enhancements are short-term, while enhancements of NO_x are long-term. The No_x enhancement events lasted almost for one year [51]. For the SPE's of August 1972, Health *et al* [52] observed the maximum ozone depletion to be about 60% in the mesosphere of the polar cap near 80 km but in the total ozone, the decrease was only 2% [53], Shumilov *et al* [54] found for ground level SPE's, a significant decrease of the total ozone in the polar cap, but no detectable effect at auroral latitudes. SPE's also seen to affect temperature and atmospheric circulation. Robble *et al* [55] estimated significant Joule heating of the mesosphere and lower thermosphere during the SPE of July 1982. On the other hand cooling was observed during SPE's at lower levels of the middle atmosphere [55,56]. Nealy *et al* [57] showed that during SPE's, there is a significant increase of the relativistic electron population in the outer trapping region with possible effects on the middle atmosphere.

Relativistic electron precipitation events (REP-electrons of hundreds of keV) occur at auroral and sub-auroral latitudes in association with magnetospheric substorms. Their duration is typically 1-3 hrs. Hale [58] reported the reversal of the fair weather atmospheric electric field during a REP event. The REP events are considered to be the dominant *in situ* source of nitric oxide in the mesosphere, and also in the upper stratosphere at sub-auroral latitudes [44]. Highly relativistic electrons (MeV energies) play a vital role in the middle atmosphere at *L*-shells of about $L =$ 3–8, *i.e.*, at sub-auroral and low auroral latitudes. Such electrons are largely absent near the solar cycle maximum, while they are prominent during the approach to solar minimum. They preferentially occur at the trailing edges of high-speed solar wind streams. They play a role mainly at heights of 40–80 km with a maximum energy deposition rate between 50 and 60 km [59]. These highly relativistic electrons (HRE) affect the ionization, conductivity, electric field and chemistry of the middle atmosphere [60]. They produce odd nitrogen and odd hydrogen. They considerably affect not only short-term, but also long-term changes of stratospheric odd nitrogen. Callis *et al* [61] showed that NO_x increase by 35–40% from 1979 to 1985 due to the action of highly relativistic electrons. This should affect the ozone concentration, as well, but this needs to be confirmed by other investigations. Sheldon [62] suggested a chain of phenomena which resulted in the influence of highly relativistic electrons on the Antarctic ozone hole formation. Goldberg *et al* [63] found, for an HRE event, the Joule heating rate > 1.5 K day near 80 km, which is more than the ozone heating rate at high latitudes An overview of information on highly relativistic electrons and their effects on the middle atmosphere was reported by Baker *et al* [60].

6.1. *Lower ionosphere :*

The lower ionosphere responds dramatically to geomagnetic storms. Its electron density is significantly enhanced, particularly in the auroral zone, which leads to a large increase of radio wave absorption and eventually, to the disappearance of radio signals in MF-HF ranges. This enhancement of electron density is caused by strongly increased precipitation of energetic particles. At mid-latitudes, these are almost eclusively electrons with energies > 20–40 keV, protons being negligible as indicated by rocket measurements [64]. There are two different types of the lower ionosphere response to geomagnetic storms. The first type, observed at high latitudes, consists of a large increase of electron density and radio wave absorption coincident with the geomagnetic storm caused by direct energetic electron injections from the magnetosphere into the auroral ionosphere.

The second type *viz.* geomagnetic storms affect considerably the lowest part of the lower ionosphere and, affect VLF/ELF radio wave propagation in the Earth-ionosphere wave guide. Geomagnetic storms improve VLF/

ELF propagation [45]. From an analysis of changes of the measured electron density profiles in the lower ionosphere during geomagnetic storms, the flux of precipitating electrons can be estimated as done by Valaskov *et al* [65] for the polar lower ionosphere. It should be mentioned that there is a region of anomalously intense particle precipitation in the Southern Hemisphere, the South Atlantic magnetic anomaly region. The effects of particle precipitation and of geomagnetic activity in the South Atlantic anomaly region are stronger than those at respective middle/moderate latitudes in the northern hemisphere.

Atmospheric electricity is mainly related to lower atmospheric layers; but since it is associated with the ionization, it is mentioned in this section. Effects of geomagnetic storms on atmospheric electricity depend to some extent on the phase of solar cycle [66]. Downward mapping of the magnetospheric and ionospheric electric fields into the atmosphere, intensifies during events associated with energetic particle precipiation [67]. The dominant contribution to the diurnal course of E_z *i.e.* the vertical component of the electric field in the auroral zone under high geomagnetic activity seems to be provided by magnetospheric/ionospheric electric field generators [68]. According to rocket measurements by Zadorozhny and Tyutin [69], the mesospheric maximum of electric field intensifies and its altitude increases with increasing geomagnetic activity at high latitudes, while there is little change at middle latitudes.

A photograph showing some typical records of atmospherics is shown in Figure 1. The records are as observed during the heavy raing days associated with a depression in the bay of Bengal. The records clearly show long period fading in the noise level both during day and night [70]. The phenomenon of fluctuating field intensity is called fading. The variations in amplitude of VLF field strengths are measured by considering the decrease below a curve surfing on the maximum noise level, while the duration is obtained by accounting the time difference between two minima on either side of the corresponding maximum and thus producing the so-called fading pattern as a whole. On seven other occasions, three during post-monsoon and four during day and night-time [70]. On all

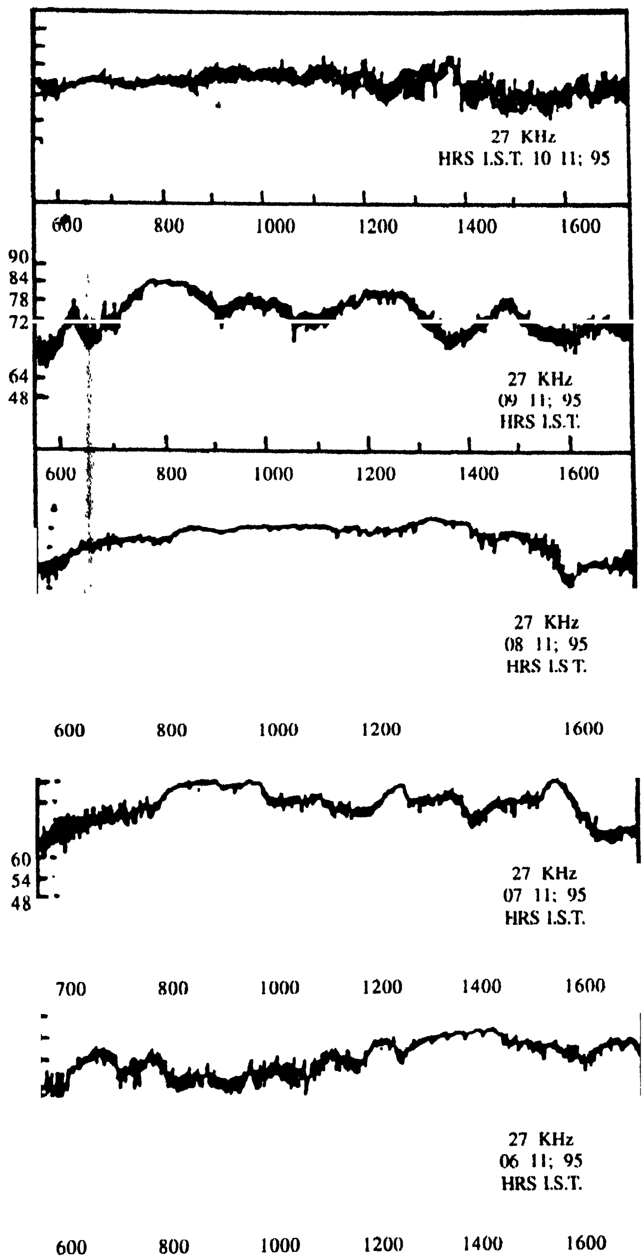

Figure 1. Typical records of atmospherics as observed over Kalyani during the heavy rainy days (6-9 November, 1995) associated with a depression in the Bay of Bengal. The ordinate is in dB above 1 μv/m. The X-axis representing the time in IST.

the occasions, the long-period fadings noticed in all atmospherics record reveal a close dependence on geomagnetic activity.

6.2. *Troposphere :*

Reviews of earlier observational correlations between the internal energy of the atmospheric system and the energy released during geomagnetic storms may be found in King

[71] and Herman and Goldberg [72]. Some expérimental findings supporting the existence of the effects of geomagnetic storms on the troposphere are presented below.

There is one peculiar feature of the geomagnetic storm effects on the troposphere; they seem to be stronger and more apparent than those on the lower and middle stratosphere. It should be noted that the IMF sector boundary effects were found to be stronger in the troposphere than in the lower middle stratosphere [43].

An atmospheric index sensitive to the degree of disturbance is the 500 hPa vorticity area index (VAI). This index responds to geomagnetic storms [73]. The effect of geomagnetic storms on the VAI was found to be stronger and more persistent than that of the IMF sector boundary crossings [73]. An analysis of statistical results on the effect of the IMF sector boundary crossing in the tropospheric vorticity area index (VAI) was made by Taylor [74]. Tinsley and Heelis [49] pointed out the principal role of strong volcanic eruptions on the appearance/ disappearance of the IMF sector boundary crossing effects in the VAI. However, there is still a controversy as regards the effects in the VAI due to their non-persistence in time.

Basic parameters *viz.* temperature, circulation and pressure, have some definite response to geomagenetic storms. A decrease of pressure after strong sporadic geomagnetic storms, particularly developed in the northern Atlantic-European and eastern Siberia-Aleutian sectors, was reported by Mustel *et al* [75]. Bucha [76] observed a decrease of surface air pressure in the northern Atlantic, a deepening of the Icelandic low, and a considerable zonalization of the 500 hPa circulation over the northern Atlantic and Europe as a consequence of geomagnetic storms due to process in the auroral oval. Pudovkin and Veretenko [77] studied changes of the meridional profile of the zonal atmospheric pressure during geomagnetic storms, and observed the effect to be maximum in auroral and subauroral zones, as expected.

Baranyi and Ludmany [78] and Bucha [79] found a coincident increase of both smoothed geomagnetic activity and smoothed temperatures in the last 100 years. Bochnicek and Pycha [80] studied correlations of 10-day, one-month and two-month average values of temperature with geomagnetic and solar activity (sunspot number). An association between meteorological storms and flare related geomagnetic storm was deduced from a consideration of storms and solar geophysical data. The values of the magnetic character figure (C_p) reveals that there might be some interrelationship between violent storms and magnetic activity. Statistically significant correlations of temperature with geomagnetic activity were found only in winter; the correlation with geomagnetic activity was better than that with solar activity, but the correlations were generally low, even though statistically significant. Bochnicek *et al* [81] found the Northern Hemisphere surface air temperature variations to be better correlated with geomagnetic activity in the *E*-phase of the QBO and with solar activity in the *W*-phase of QBO. Similar investigations may be found in Bochnicek *et al* [81], who tried to find regions of significant positive or negative temperature deviations from long-term averages caused by geomagnetic storms. A critical review of sun-weather relationships was written by Pittock [82] from the point of view of a 'non-believer'. A very comprehensive and careful analysis, and an overview of statistical approaches and their results as applied particularly to the IMF sector boundary crossing effect on VAI, but with generally valid conclusions for sun-weather studies, was given by Taylor [83], from the point of view of neither a 'beliver' nor a 'non-believer'. A recent review by Roederer [84] showd progress in sun-weather relationships, including solar wind high energy paritcle effects, paritcularly to the reliability of the statistical results. The principal short age of sun-weather studies is a lack of relevant and generally accepted physical mechanism to explain sun-weather relationship.

During September 1978, torrential rain started on the 27th and continued till the 29th in West Bengal in India. The downpour during the period surpassed all previous record of 100 years and the whole of West Bengal experienced devastating flood havoc. In the atmospherics record, we observed long period fading in the nose level closely associated with the meteorological activity during the flood-rainy days. Ovservations of barometric pressure, temperature, dew point, vapour pressure and relative humidity for a few days preceding and following for flood-rainy days, have been considered. These allied meteorological parameters of interest were recorded over

Kolkata at three specific hours : 0830 (morning), 1130 (noon) and 1730 (evening) in addition to the 24-h reainall ending at 0830 a.m. on each date. The mean values of these parameters are plotted in Figure 2. The number of

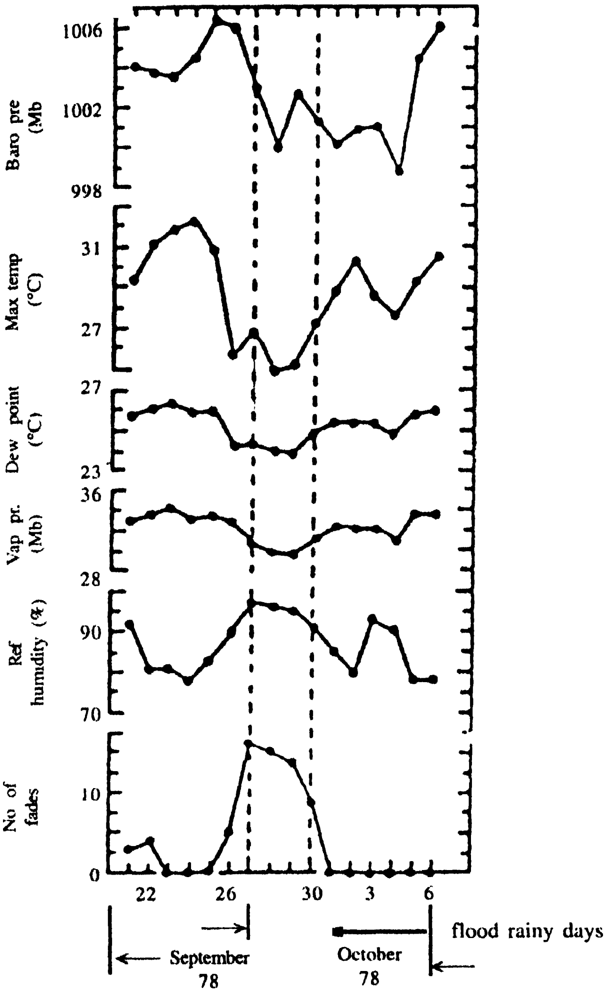

Figure 2. Variations of different meteorological parameters with number of fades in atmospherics record during the flood rainy days. (The data for geomagnetic character figure C_p values are obtained from solar geophysical data book published from NOAA, USA).

occurrences of the fades against the corresponding date is also shown in the same figure. The figure clearly shows that there is an almost simultaneous fluctuation of all the above parameters during the monsoon acitivity of 27–30 September, 1978 [70]. Such a long-period fading was also observed on other occasions of low pressure depressions in the Bay of Bengal. An examination of the data during the flood-rainy days indicated a close association of the meteorological activity with geomagnetic storms. From the analysis, it was reproted that the peak of flare activity might be responsible for the chain of solar terrestrial events, eventually resulting in the torrential rains. It may well be that the charged particles emitted by the flare region of the sun arrived at the earth's upper atmosphere about a day letter, producing a first peak in solar-wind flux. The solar wind on arriving at the polar regions, started a geomagnetic storm on 25th September, 1978. The heating of the polar atmosphere by magnetic storm particles may give rise to gravity-wave perturbations which travelled to equatorial regions on 27th September, when the heavy downpour started [70].

7. Electric and magnetic fields due to thunderclouds and lightning from cloud-top to ionosphere

Sprites and elves are tow classes of phenomena which are observed after and above some strong lightning flashes from especially energetic thunderclouds [85]. To understand the physical process responsible for these spectacular events, Cho and Rycroft [86] have developed both a quasi-electrostatic code and an electromagnetic code to model the temporally and spatially varying electric and magnetic fields in the atmosphere above the cloud and in the ionosphere follwing a large, positive cloud-to-ground lightning discharge. Many scientists around the world have performed similar or relared studies [87,88].

In the modeling studies, Maxwell's equations of electromagnetism are solved using appropriate boundary conditions and grids, to find the electric field in the atmosphere and ionosphere where the variation of conductivity is a function of altitude. The redistribution of electric charge and the electromagnetic pulse due to lightning, are both responsible for electric fields which can accelerate electrons. These heated electrons collide with neutrals and ions, heating them and ionising the atmosphere. Runway electrons may be formed and the electrical breakdown of the atmosphere may occur. Results of the electromagnetic simulation code for +200 coulomb cloud-to-ground discharge, with a characteristic time scale of τ ~25 μs, satisfactorily explain many features of red sprite phenomena, particularly the expanding ring of light near 90 km altitude. Additional results reveal that (i) these process are strongly nonlinear; (ii) more than 2 ms after the discharge, the electric field everywhere above the cloud top and into the ionosphere is positive downward, *i.e.* in the same direction as the fair weather field; (iii) the detailed temporal evolution of the pimple on the bottom of the ionosphere (at heights of 70 and 80 km) has been estimated; (iv) the ELF spectrum of the atmospheric associated with such a large positive cloud-to-ground discharge is strong near 10 Hz and between 100 and 300 Hz which explains both the *Q*-burst and the strong slow tail component of the atmospherics responsible for red sprite phenomena in the lower ionosphere.

8. Electrostatic thundercloud fields

The penetration of electrostatic (ES) thundercloud fields in to the lower ionosphere were studied by many authors [89,90]. Experimental evidences show that ES fields are capable of maintaining the ionospheric electrons at a persistently heated level well above their ambient thermal energy [90]. Changes in the thundercloud charge distributions lead to heating above this quiescent level, and the corresponding changes in the lower ionospheric conductivity are registered as fast perturbations of subionospherically travelling VLF signals [91]. The electrostatic heating (ESH) model does not consider lightning descharges, rather it concentrated on integrated long term effects of quasi-static charge systems in thunderstorms. The model is valid with good accurancy as long as lightning discharges remove only a small fraction of the total charge accumulated in thunderstorm. The lower ionospheric conductivity can be modified owing to heating, up to one order o magnitude in regions with characteristic lateral extent of ~150–350 km. The vertical extent of the heated region in ~10 km, at altitudes of ~70–80 km, reaching even more than 85 km in some cases depending on the ambient conductivity profile. The electron heating may change the chemical balance in the *D*-region and the magnitude of electrostatic thundercloud fields to map higher ionospheric altitudes.

9. Conclusion

In the Earth's troposphere, there are a large number of electric generatic mechanisms of which the thunderstorm (and the associated lightning) is considered to be the most prominent one to produce global geophysical effects. The electromagnetic energy radiated from lightning propagates through the space between the ionosphere and the Earth in the wave guide transmission mode or in the ray, mode, reflecting between them. The entire gamut of terrestrial energy resources and associated systems owe their origin directly or indirectly to the Sun. In order to exploit fully the benefits of our radio environment, it is necessary to predict the solar variability and quantify the consequent variations in the ionospheric characteristics. Ionosphere affects radio communication in every band of frequency, currently in use.

The production of charged particles in the ionosphere depends upon the abundance of ionisable constituents as well as ionising radiations. The loss depends on the density of neutral atmosphere, especially the molecular constituents. The solar controlled conductivity variations in the lower stratosphere over the thunderstorms, control the current flow in the global circuit. This may ultimately influence cloud physical processes and thereby the atmospheric energy. The solar modulation of the Earth's electric field takes place through regulation of ionising radiation. Lower mesosphere and stratosphere appear to be regions where the solar signal interacts with the lower atmosphere.

10. Scope of further investigation

A comparison of atmospheric radio noise field strength (ARNFS) values with thunderstorms of the Eastern region of India at day-time and night-time, exhibits good agreement [5]. This observation may be extended for the entire landmass of India following similar procedure to investigate the role of thunderstorm electricity in affecting the tropical radio noise level.

Though lightning is apparently an important atmospheric electrical stimulus, solar control of ionization above thunderstorms may ultimately modulate atmospheric energetics. It is known that WT radio waves, such as those generated by lightning, can cause trapped particles to be dumped into the atmosphere by destabilizing plasma in the magnetosphere. Presently, we have a concept where solar controlled variation of stratospheric ionization explains atmospheric electrical variations and possibly other relevant meteorological parameters. The possibility of variable solar activity modulating thunderstorm and lightning activity which in turn, influences other parts of meteorology, needs to be further investigated both theoretically and from the results of statistical studies [5].

When observations are taken during the sunspot minimum, the occurrences of solar radio burst are expected to be small. Obviously during the next sunspot minimum years if multiwavelength observations are taken, it may provide valuable information of solar radio bursts and its consequences over the atmosphere. In addition to radiometer and spectrographic observations, it is extremely important to be able to record images of the brightness distribution and polarization of the radio emission of the Sun at a number of frequencies, for which, a big array of microwave dish antennas are required. Then, one can examine the locations of various microwave features relative to the magnetic field and to visible and EUV emissions. The top priority should be given to the coincident analysis and modeling of microwave, hard X-rays, and $H\alpha$ emission to study in particular, the spectral and temporal evolution of electron populations responsible for microwave emissions and the role of inhomogeneities. Also one should investigate the short duration spikes and their relationship to peculiarities in other spectral ranges and to study the millimetric emission regarding its spectrum, its location relative to magnetic structures, and the fast intensity changes which are belived to originate from elementary electron bursts injected into the solar atmosphere during flares [92]. To achieve these goals, existing techniques and instrumentation will have to be improved and new instruments need to be built [93].

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Abouth the Reviewers

Dr. Sanjib Kumar Kar did his B. Sc. and M. Sc. in Physics from Kalyani University in the year 1990 and 1992 respectively. He also did his Ph. D. in Atmospheric Physics from the same University. After that he joined the National Central University, Taiwan as a post doctoral fellow. In 2002, he was awarded the KOSEF post doctoral fellow and joined the Department of Atmospheric Sciences, Pusan National University. He also visited the institut Fur Chemie und Dynamik der Geosphare II : Troposphare, Forschungszentrum, Juelich as a visiting scientist. He has published more than ten papers in National and International journals. His field of interest is Atmospherics, GPS meteorology, Thunderstorm and Lightning.

Prof. A B Bhattacharaya did his M. Sc. in Physics from Calcutta University and Post Doctorate from MIT, USA. Presently he is the head of the Department of Physics, Kalyani University. He has published over 85 papers in reputed journals and more than 50 papers in symposia/ Conferences. He has written 10 text Books for Science and Engineering degree students. He has supervised many Ph. D. students and conducted many research schemes. His field of interest is atmospherics, radio wave propagation, Solar radio astronomy and multimesh topology.

Prof. Yuei-An Liou did his M. S. in Atmospheric and Space Sciences from University of Michigan and Ph. D. from the same university. He has published about 25 referred papers and more than 50 international conference papers. He has conducted many research projects. His field of interest is GPS meteorology and ionosphare, Remote sensing of the atmosphare and land surface, Land Surface processes modeling, Application of neural network and fuzzy systems.